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Heavy flavour spectroscopy at LHC

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ABSTRACT

The pp collision data collected in the LHC Run I provides a great opportunity for heavy flavour studies. The latest results on exotic states, heavy baryon and B_c^+ mesons are reviewed.

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1 Introduction

Thanks to the large center-of-mass energy available at the LHC, $b\bar{b}$ and $c\bar{c}$ pairs are produced prolifically, which provides great opportunities for studying the production and properties of heavy hadrons. This is not only important itself as tests and inputs to QCD models, but also because they have to be well understood as the Standard Model background in the search for new physics. The major LHC detectors are complementary to each other in the study of heavy flavour spectroscopy by covering different acceptance and kinematic ranges: general purpose detectors like ATLAS and CMS cover high p_T and low rapidity range, while the forward spectrometer LHCb has access to lower p_T and higher rapidity region. This proceeding reports recent results from these experiments, on exotic states, heavy baryons and B_c^+ meson.

2 Exotic states

The exotic state that attracts a lot of attention recently is the charged charmonium-like $Z(4430)^-$. This state was first reported as a $\psi(2S)\pi^-$ bump in $B^0 \rightarrow \psi(2S)\pi^- K^+$ by Belle collaboration in 2008; BaBar collaboration could explain the enhancement as a reflection of the known K^* states, but did not rule out the existence of $Z(4430)^-$ either. With a B^0 signal yield an order of magnitude larger than BaBar or Belle detectors have, LHCb collaboration performs a full amplitude analysis considering known K^* states, and observe the $Z(4430)^-$ with a significance larger than 13.9σ , as shown in Figure 1 [1]. The Argand diagram of the $Z(4430)^-$ amplitude (Figure 1) shows the resonance behaviour for the first time. The spin-parity is measured to be 1^+ , by excluding $0^-, 1^-, 2^-, 2^+$ hypotheses by at least 9.7σ . For a charged charmonium state, $Z(4430)^-$ has a minimum quark content of $c\bar{c}d\bar{u}$, which clearly does not fit into traditional quark model.

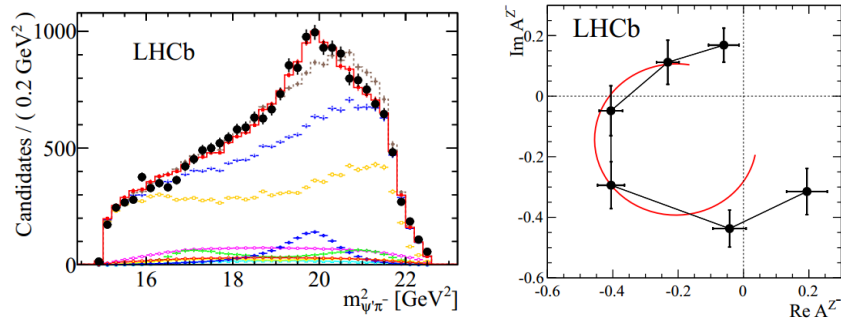


Figure 1: (Left) Distribution of $m_{\psi(2S)\pi^-}^2$. Black dots are data, the red solid and brown dashed lines represent the total fit with and without the $Z(4430)^-$ component. (Right) Fitted values of $Z(4430)^-$ amplitude in six $m_{\psi(2S)\pi^-}^2$ bins shown in an Argand diagram.

$X(3872)$ is the first charmonium-like exotic state ever observed. Its quantum number is finally pinned down to 1^{++} in 2013 [2, 3], but the nature is still unclear, drawing a lot of theoretical interests. Useful information can be obtained from its radiative decay since various interpretations predict very different values for the ratio $R_{\psi\gamma} \equiv \mathcal{B}(X(3872) \rightarrow \psi(2S)\gamma) / \mathcal{B}(X(3872) \rightarrow J/\psi\gamma)$. LHCb lately finds a 4.4σ evidence of $X(3872) \rightarrow \psi(2S)\gamma$ decay in $B^+ \rightarrow X(3872)K^+$ [4] (as shown in Figure 2), and measured its branching fraction relative to $X(3872) \rightarrow J/\psi\gamma$: $R_{\psi\gamma} = 2.46 \pm 0.64 \pm 0.29$, where the first uncertainty is statistical and the second systematic, as followed in the rest of the proceeding. This result is consistent with expectations of a charmonium $c\bar{c}(2^3P_1)$ or a molecule-charmonium mixture interpretation, but does not support a pure $D\bar{D}^*$ molecule interpretation.

A search for the bottomonium counterpart of $X(3872)$ is recently performed in $X_b \rightarrow \Upsilon(1S)\pi^+\pi^-$, $\Upsilon(1S) \rightarrow \mu^+\mu^-$ decay by CMS [5]. No evidence of X_b is observed, and upper limits are set at 95% confidence level

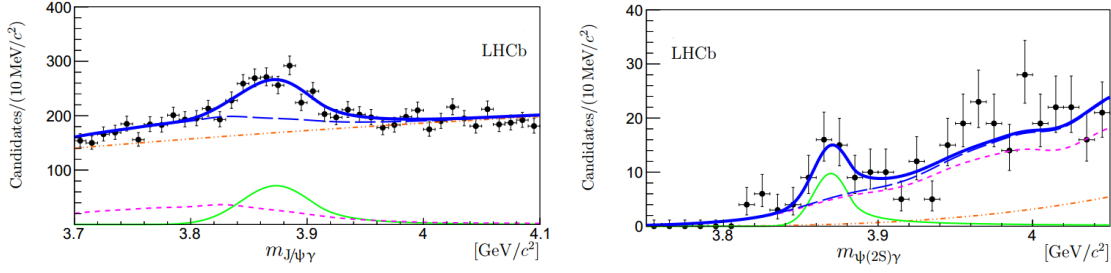


Figure 2: Invariant mass distributions of (left) $J/\psi\gamma$ and (right) $\psi(2S)\gamma$ from B decays.

on the ratio $R_{X_b} \equiv \sigma(pp \rightarrow X_b \rightarrow \Upsilon(1S)\pi^+\pi^-)/\sigma(pp \rightarrow \Upsilon(2S) \rightarrow \Upsilon(1S)\pi^+\pi^-)$ as a function of X_b mass (Figure 3). The upper limits are in the range of 0.9 – 5.4% for X_b mass between 10 and 11 GeV.

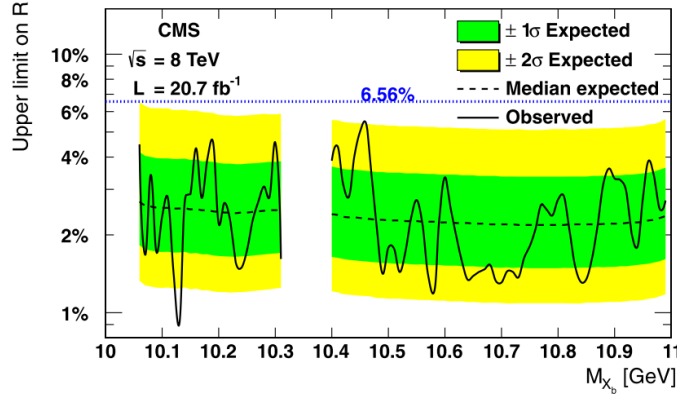


Figure 3: Upper limit at the 95% confidence level on R_{X_b} (see definition in text) as a function of X_b mass.

3 Heavy baryons

According to the Heavy Quark Expansion (HQE) theory, the b baryon lifetime is expected to be close to that of the B mesons, and $\tau(\Lambda_b^0)/\tau(\bar{B}^0)$ should differ from unity by no more than a few percent. However LEP results indicate this ratio is much smaller, which became a puzzle for the last decade. With pp collision data at $\sqrt{s} = 7$ TeV, ATLAS [6] and CMS [7] determined Λ_b^0 lifetime, resulting in a ratio over B^0 lifetime much closer to one with large uncertainties. LHCb precisely measures $\tau(\Lambda_b^0)/\tau(\bar{B}^0)$ with 1 fb^{-1} data [8] and the result is consistent with HQE prediction. Lately LHCb updated this measurement with 3 fb^{-1} full data from Run I [9]. Figure 4 shows the reconstructed Λ_b^0 and \bar{B}^0 signals using similar decay final states $\Lambda_b^0 \rightarrow J/\psi p K^-$ and $\bar{B}^0 \rightarrow J/\psi \bar{K}(892)^*0 (\bar{K}(892)^*0 \rightarrow \pi^+ K^-)$, as well as their yield ratio as function of decay time. The lifetime ratio is measured to be $\tau(\Lambda_b^0)/\tau(\bar{B}^0) = 0.974 \pm 0.006 \pm 0.004$. This agrees with previous LHCb result and HQE prediction, and gives the most precise Λ_b^0 lifetime measurement using $\tau(\bar{B}^0)$ world average. In another measurement of $\tau(\Lambda_b^0)$, LHCb uses a different decay channel of $\Lambda_b^0 \rightarrow J/\psi \Lambda$ with 1 fb^{-1} [10]. Combined result gives $\tau(\Lambda_b^0) = 1.468 \pm 0.009 \pm 0.008$ ps. The latter analysis also gives the most precise single measurement of B^+ , B^0 and B_s^0 (effective) lifetime, as listed in Table 1.

Unlike the Λ_b^0 state, the bottom strange baryons such as Ξ_b and Ω_b are less abundantly produced, hence less studied. LHCb lately measured their lifetime, using $\Xi_b^- \rightarrow J/\psi \Xi^-$ and $\Omega_b^- \rightarrow J/\psi \Omega^-$ channels, with subsequent decays of $\Xi^- \rightarrow \Lambda \pi^-$, $\Omega^- \rightarrow \Lambda K^-$, $\Lambda \rightarrow p \pi^-$ and $J/\psi \rightarrow \mu^+ \mu^-$ [11]. The reconstructed mass and decay time of Ξ_b^- and Ω_b^- are shown in Figure 5, their lifetime are measured to be $\tau(\Xi_b^-) = 1.55^{+0.10}_{-0.09} \pm 0.03$ ps

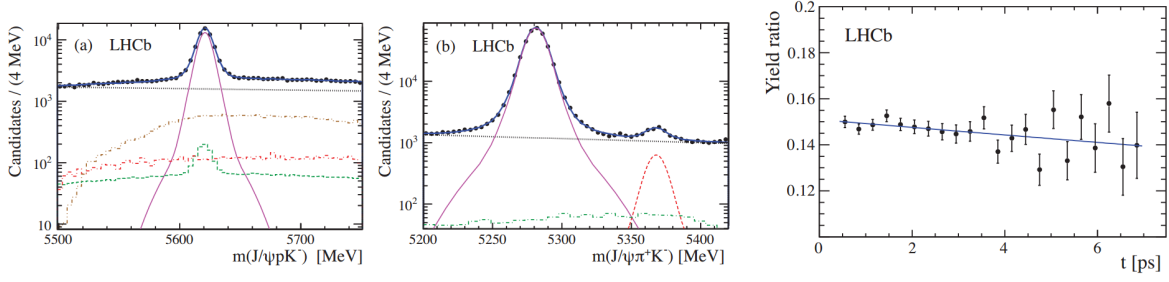


Figure 4: Fits to invariant mass distribution of (left) $J/\psi p K^-$ and (middle) $J/\psi \pi^+ K^-$ combinations. The solid purple lines represents the fitted Λ_b^0 and \bar{B}^0 signals. (Right) The yield ratio of $N(\Lambda_b^0)/N(\bar{B}^0)$ as a function of decay time.

Lifetime	Value (ps)
$\tau_{B^+ \rightarrow J/\psi K^+}$	$1.637 \pm 0.004 \pm 0.003$
$\tau_{B^0 \rightarrow J/\psi K^{*0}}$	$1.524 \pm 0.006 \pm 0.004$
$\tau_{B^0 \rightarrow J/\psi K_S^0}$	$1.499 \pm 0.013 \pm 0.005$
$\tau_{\Lambda_b^0 \rightarrow J/\psi \Lambda}$	$1.415 \pm 0.027 \pm 0.006$
$\tau_{B_s^0 \rightarrow J/\psi \phi}$	$1.480 \pm 0.011 \pm 0.005$

Table 1: Measured B^+ , B^0 , Λ_b^0 and B_s^0 (effective) lifetime as in Ref. [10].

and $\tau(\Omega_b^-) = 1.54_{-0.21}^{+0.26} \pm 0.05$ ps. These are the most precise measurements to date, consistent with CDF results [12, 13] and with theoretical predictions.

4 B_c^+ physics

The B_c^+ state is the ground state of a family of unique mesons that consist of two different heavy flavour quarks. Its production cross-section at the LHC is expected to be an order of magnitude larger than it was at Tevatron (where it was discovered), and this allows more detailed study on its properties. Using the final states of $B_c^+ \rightarrow J/\psi \pi^+$, the ratio $R_\sigma = \sigma(B_c^+) \mathcal{B}(B_c^+ \rightarrow J/\psi \pi^+) / \sigma(B^+) \mathcal{B}(B^+ \rightarrow J/\psi K^+)$ is measured by LHCb [14] and CMS [19] in different kinematic regions as shown in Table 2. The dominating systematic uncertainties for R_σ measurements come from the uncertainty of B_c^+ lifetime which was measured only at Tevatron. However this situation has been changed lately, since LHCb measured the lifetime with better precision: $\tau(B_c^+) = 509 \pm 8 \pm 12$ fs [15] using semileptonic decay $B_c^+ \rightarrow J/\psi \mu^+ \nu$. Figure 6 shows the results of simultaneous fits to the distributions of reconstructed B_c^+ pseudo decaytime and invariant mass of the $J/\psi \mu^+$ combinations. The pseudo decaytime is defined as $\mathbf{p} \cdot (\mathbf{v} - \mathbf{x}) M_{3\mu} / |\mathbf{p}|^2$, where \mathbf{p} is the three-momentum of the $J/\psi \mu$ system in the laboratory frame, and \mathbf{v} and \mathbf{x} are the measured position of the B_c^+ decay and production vertices. This improvement will benefit many other B_c^+ measurements such as its mass and decay branching ratios.

The B_c^+ mesons are expected to decay via many modes: either c or \bar{b} quark decays weakly with the other as spectator, or they can annihilate. Only very few channels are experimentally observed before the operation of LHC due to the small production cross-section available. Nowadays the list of observed decays has been expanded, mostly by LHCb, including observation of the very first c quark decay $B_c^+ \rightarrow B_s^0 \pi^+$ [16], as shown in Figure 7. For \bar{b} quark decay the list of new channels is longer, the latest being observation of $B_c^+ \rightarrow J/\psi K^+ K^- \pi^+$ [17] and a 4.5σ evidence of $B_c^+ \rightarrow J/\psi 3\pi^+ 2\pi^-$ decay [18] (as shown in Figure 8). CMS recently observed $B_c^+ \rightarrow J/\psi \pi^+ \pi^- \pi^+$ [19] and measured its branching fraction relative to $B_c^+ \rightarrow J/\psi \pi^+$, the result consistent with LHCb result [20].

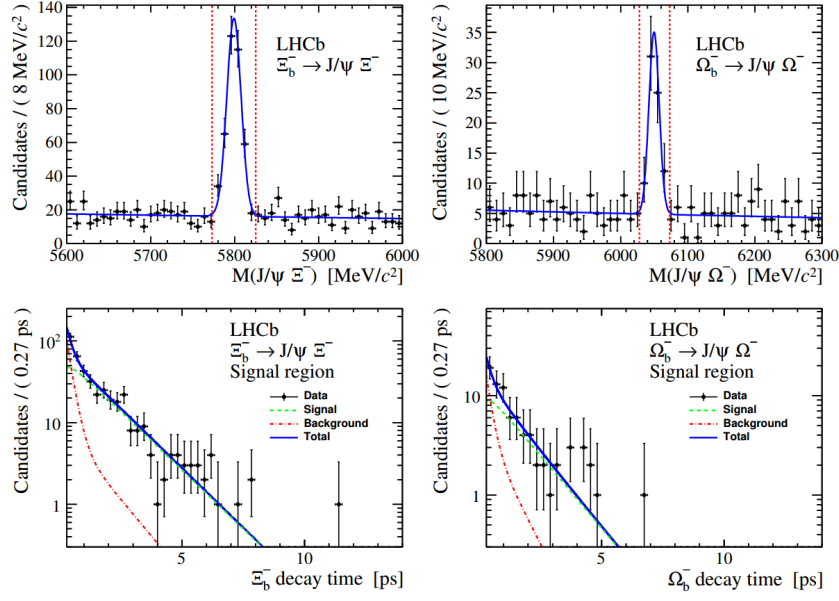


Figure 5: (Top) Invariant mass of (left) $J/\psi \Xi^-$ and (right) $J/\psi \Omega^-$ combinations. (Bottom) Decay time of reconstructed (left) Ξ_b^- and (right) Ω_b^- candidates.

Experiment	$R_\sigma = \frac{\sigma(B_c^+) \mathcal{B}(B_c^+ \rightarrow J/\psi \pi^+)}{\sigma(B^+) \mathcal{B}(B^+ \rightarrow J/\psi K^+)}$	Kinematic range
LHCb [14]	$(0.68 \pm 0.10 \pm 0.03 \pm 0.05)\%$	$p_T > 4 \text{ GeV}, 2.5 < \eta < 4.5$
CMS [19]	$(0.48 \pm 0.05 \pm 0.04 \pm 0.05)_{-0.03}^{+0.05}\%$	$p_T > 15 \text{ GeV}, y < 1.6$

Table 2: R_σ measured at different kinematic ranges, where the uncertainties are statistical, systematic and that caused by uncertainty on B_c^+ lifetime using world average.

5 Conclusions

The LHC experiments have been fruitful at heavy flavour spectroscopy studies. This proceeding reviews some latest highlights, including observation of a charged charmonium-like state $Z(4430)^-$, study of the $X(3872)$ radiative decays, more precise determination of b -baryon lifetimes, and a better understanding of the B_c^+ properties. As the analysis of Run I data still ongoing and Run II at higher center-of-mass energy is starting soon, more interesting results will keep coming out to gain us more knowledge on the heavy hadron spectroscopy.

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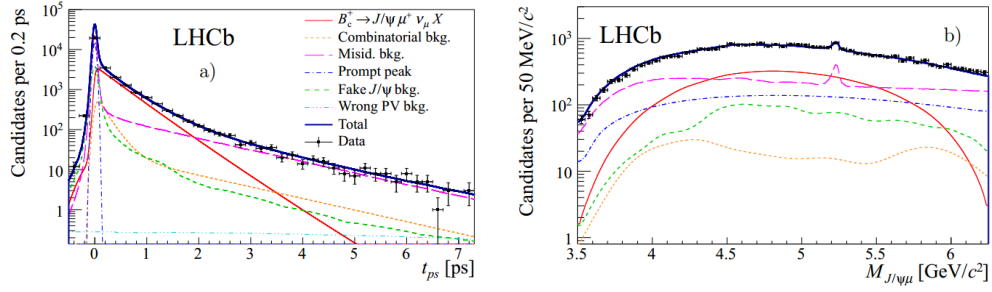


Figure 6: (Left) Pseudo decaytime of reconstructed B_c^+ candidates; (right) invariant mass distributions of $J/\psi\mu$ combinations.

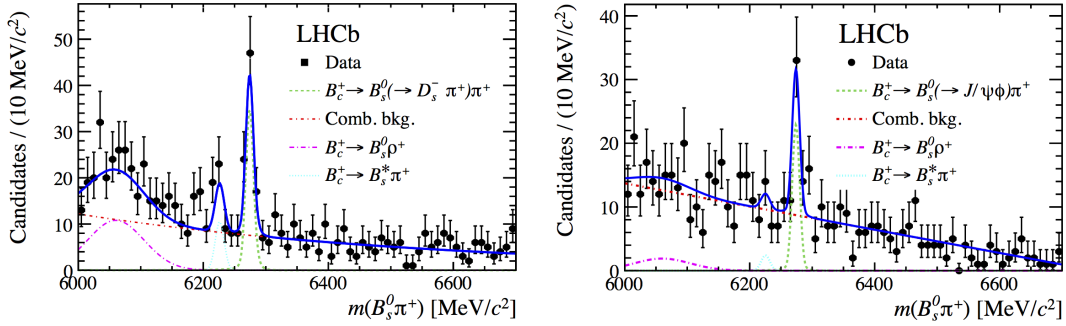


Figure 7: Invariant mass of $B_s \pi^+$ combination, using (left) $B_s^0 \rightarrow D_s^- \pi^+$ and (right) $B_s^0 \rightarrow J/\psi \phi$ final states respectively.

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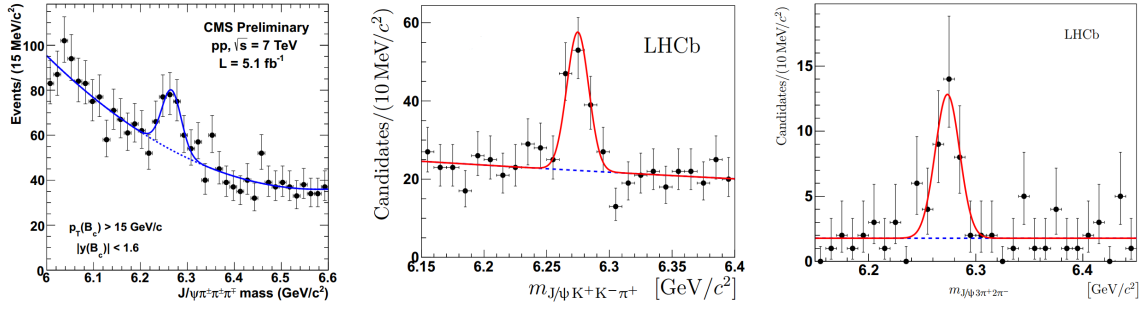


Figure 8: Mass distributions of the B_c^+ candidates reconstructed from (left) $J/\psi \pi^+ \pi^- \pi^+$, (middle) $J/\psi K^+ K^- \pi^+$ and (right) $J/\psi \pi^+ \pi^+ \pi^- \pi^-$ decays.